A zero emission concept analysis of a single family house: Part 2 sensitivity analysis

Houlihan Wiberg, A. A. M., Georges, L., Fufa, S. M., Risholt, B. D., & Good, C. S. (2015). *A zero emission concept analysis of a single family house: Part 2 sensitivity analysis*. SINTEF akademisk forlag. https://www.sintefbok.no http://hdl.handle.net/11250/2386611

ZEB Project report 21 – 2015

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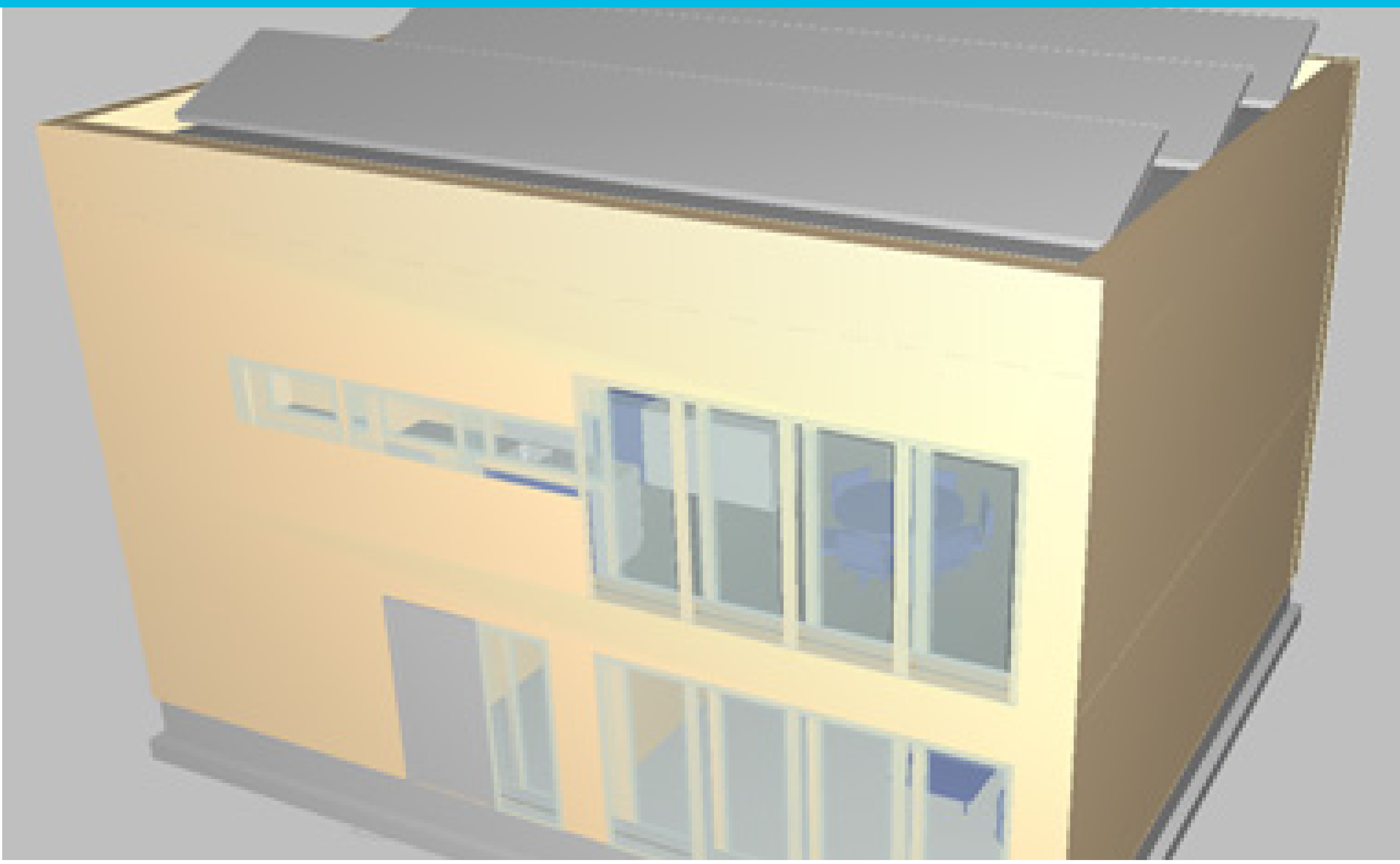
The Research Centre on
Zero Emission Buildings



SINTEF Academic Press

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Keywords:
Zero emission building, residential concept building, embodied emissions, green house gas emissions, environmental product declarations, construction materials, electricity demand, CO_2 factors, generic and specific data

ISSN 1893-157X (online)
ISSN 1893-1561
ISBN 978-82-536-1449-6 (pdf)
ISBN 978-82-536-1450-2 (printed)

Illustration on front page:
Sofie Mellegård, SINTEF Building and Infrastructure

Norwegian University of Science and Technology [1)]
N-7491 Trondheim
Tel: +47 73 59 50 00
www.ntnu.no
www.zeb.no

SINTEF Building and Infrastructure Trondheim [2)]
Høgskoleringen 7 b, POBox 4760 Sluppen, N-7465 Trondheim
Tel: +47 73 59 30 00
www.sintef.no/byggforsk
www.zeb.no

SINTEF Academic Press
c/o SINTEF Building and Infrastructure Oslo
Forskningsveien 3 B, POBox 124 Blindern, N-0314 Oslo
Tel: +47 73 59 30 00
www.sintef.no/byggforsk
www.sintefbok.no

Acknowledgement

This report has been written within the *Research Centre on Zero Emission Buildings* (ZEB). The authors gratefully acknowledge the support from the Research Council of Norway, BNL – Federation of construction industries, Brødrene Dahl, ByBo, DiBK – Norwegian Building Authority, Caverion Norge AS, DuPont, Enova SF, Entra, Forsvarsbygg, Glava, Husbanken, Isola, Multiconsult, NorDan, Norsk Teknologi, Protan, SAPA Building Systems, Skanska, Snøhetta, Statsbygg, Sør-Trøndelag County Authority and Weber.

Abstract

This report presents the results from a sensitivity analysis regarding the influence of using emission data from Norwegian EPD's instead of the generic data from Ecoinvent, using different CO_{2eq}-factors (for electricity in the operational phase) and electricity load from household appliances on the overall ZEB residential building performance.

The materials which contribute the most to the embodied greenhouse gas emissions in the original ZEB concept residential building were selected [1]. The sensitivity analysis is performed by replacing the generic Ecoinvent data with Norwegian EPD data where available. Even though the embodied emissions from PV contribute the most emissions, they are not included in this analysis due to the lack of Norwegian EPD data for PV. Instead, the influence of different PV technologies and different module orientations on the embodied and avoided emissions is incorporated. Even if the calculation of embodied emission has uncertainties, the results indicate the annual embodied emissions reduction from 7.2 kg CO_{2eq}/m^2 to 5.8 kg CO_{2eq}/m^2 when the generic data is replaced with Norwegian EPD data.

In addition, the sensitivity study investigates the influence of CO_{2eq}-factors for electricity in the operational phase on the emission balance. Furthermore, the analysis discusses the energy consumption of electric appliances and how it could be reduced through more efficient products, especially the hot-fed machines (i.e. washing machines, tumble dryer and dishwasher). The ZEB Centre has chosen an average CO_{2eq} factor of 132 g CO_{2eq}/KWh for electricity in the operational phase of the building's lifetime of sixty years. ZEB ambition level ZEB-OM can still not be reached for the residential concept building. However, to choose higher European CO_{2eq} factors make it possible to achieve this ambition.

In further work, the calculation of embodied emissions using Norwegian EPD data for other construction materials should be incorporated. In the second stage of the work, the system boundary should be extended to include end of life emissions. There is further potential to reduce the embodied emissions by considering the biogenic carbon stored in wood products and the use of alternative building materials should also be considered. In addition, further work is thus required to define the potential energy saving that would result from a shift of standard appliances to high-performance appliances with better energy efficiency.

Contents

1. Introduction

1.1 Background

This concept work started with the analysis of two simplified shoebox models late autumn 2011 for both an office and residential building. In the start of 2012, it was decided to design more realistic building models with a typical two storey single family house was chosen for the residential concept work. A complete study of the energy concept, as well as, embodied emissions for the residential building was carried out in 2012 and 2013. The results from this study is published in the ZEB report no. 9 entitled *A zero emission concept analysis of a single family house* published in 2013 [1]. The calculations of embodied emissions from the construction materials and components were based on generic material data from the Ecoinvent database.

This report presents the results from a sensitivity analysis regarding the embodied emissions of selected construction materials, as well as, different CO_{2eq} factors for the payback of CO_{2eq} emissions over the building's lifetime. The impact of reduced loads from electrical appliances is also included.

The sensitivity analysis has been a part of the ZEB Centre's research programme in 2014 whereby the research has been conducted by researchers at NTNU and SINTEF. In addition, a number of ZEB's industry partners have contributed by making Environmental Product Declarations (EPD) available for the researchers.

1.2 Aim and scope of the work

The concept study has been carried out as interdisciplinary research involving architects, mechanical engineers, construction engineers, materials and LCA experts. The framework for the study is the objective of the Norwegian Research Centre on Zero Emission Buildings aimed at buildings that over the building lifetime result in no greenhouse gas emissions.

While the original study used generic material data, the sensitivity analysis of embodied emissions utilizes specific material data found in Environmental Product Declarations (EPDs) for materials and components that are available in the Norwegian market. Many of the EPDs are for materials manufactured by industry partners of the ZEB centre. The report therefore presents both data on the sensitivity of embodied emissions in materials, as well as the impact of using specific construction products manufactured in Norway.

The results of the original study found that some materials and components have larger impact on the embodied emissions than others [1], and the sensitivity study focuses on these materials and components that result in high emissions.

The original report also presented the need to investigate further the impact of the CO_{2eq} factor on the overall emission balance. The report therefore also includes a sensitivity analysis on the effects of using different CO_{2eq} factors for energy use and renewable energy compensation in operation.

Finally, the electricity use for household appliances was found to be a major load for the building. These electricity needs were taken as representative for the average energy consumptions of existing households. No effort has been taken to minimize this load and consider high-performance equipment. Therefore the potential of electricity reduction for household appliance is discussed, especially as regards the implementation of so-called hot-fed machines for washing machines, clothes dryers or dishwashers.

The main research question for the sensitivity study is to investigate if it is possible to achieve a ZEB-OM ambition level if the concept building is calculated using Norwegian EPD data rather than generic Ecoinvent data. A secondary question is to analyse the effect of using different CO_{2eq} factors for the electricity used in operation and see how this factor affect the ZEB ambition level for the residential concept building.

1.3 About the report

As stated in the background chapter, this is part 2 of the ZEB report no. 9 *A zero emission concept analysis of a single family house,* published in 2013. Short excerpts from the original report are included to make it possible to read this subsequent report without having access to the original report.

This report is divided into six chapters. After the introductory chapter, three subsequent chapters summarise the first part of the concept model study. The results of the sensitivity study are found in chapter 5 and all discussions and conclusions are found in chapter 6.

1.4 Simulation tools and methods used

The 3D architectural drawings and 3D BIM modelling have been done using Revit version 2012 Embodied emission and embodied energy calculation have been done using the LCA Software tool SimaPro version 7.3.3 [2] which use data from the Ecoinvent v.2.2 database [3]. Material quantities have been imported from the Revit BIM-model, via Excel.

Simulation of annual heating and cooling demand, peak heating and cooling load, net energy budget, heat loss calculation, thermal comfort simulation and CO_2-level simulation have been done in SIMIEN version 5.011 [4]. Thermal bridge calculations have been done in the numerical software tool Therm [5].

Performance calculations of the air source heat pump combined with solar thermal collectors have been done using PolySun [6]. Performance of the PV-systems has been calculated with simplified spreadsheet models (Excel), but is verified by the PV-tool PV-syst [7].

1.5 ZEB-definition and different ZEB- levels

A revised definition of ZEB is currently been defined. The current definition is based on additional criteria [8]:

- Ambition level
- System boundaries
- CO_2eq-factors
- Energy concept
- Embodied emissions
- Emissions form construction, operation and end of life
- Verification in use

These criteria will not be explained in detail in this paper apart from a brief explanation of the minimum requirements on energy efficiency and ambition levels currently being defined. The minimum requirements on energy efficiency are proposed to be in accordance with those stated in NS 3700 [9].

Figure 1.1 illustrates how the different ambition levels take into account different emission items. The orange circles illustrate emissions from different phases of a building's lifetime. The green circles show how renewable energy generation offset emissions. The following five ambition levels are defined as:

1. ZEB-O÷EQ: Emission related to all energy use except the energy use for equipment (appliances) shall be zero. Energy use for equipment is often regarded as the most user dependent, and difficult to design for low energy use.
2. ZEB-O: Emission related to all operational energy use shall be zero, also energy use for equipment. This is shown as the dark green circle in figure 1.1. The renewable energy production is sufficient to offset all emissions form operation of the building.
3. ZEB-OM: Emission related to all operational energy use plus all embodied emission from materials and installations shall be zero (medium green renewable energy generation, see figure 1.1). This is the level we aiming to achieve in this study.
4. ZEB-COM: Same as ZEB-OM, but also taking into account emissions related to the construction process of the building.
5. ZEB-COME: Same as ZEB-COM though emissions related to a scenario for the end-of-life phase "E" have to be included and compensated for (light green circle in figure 1.1)

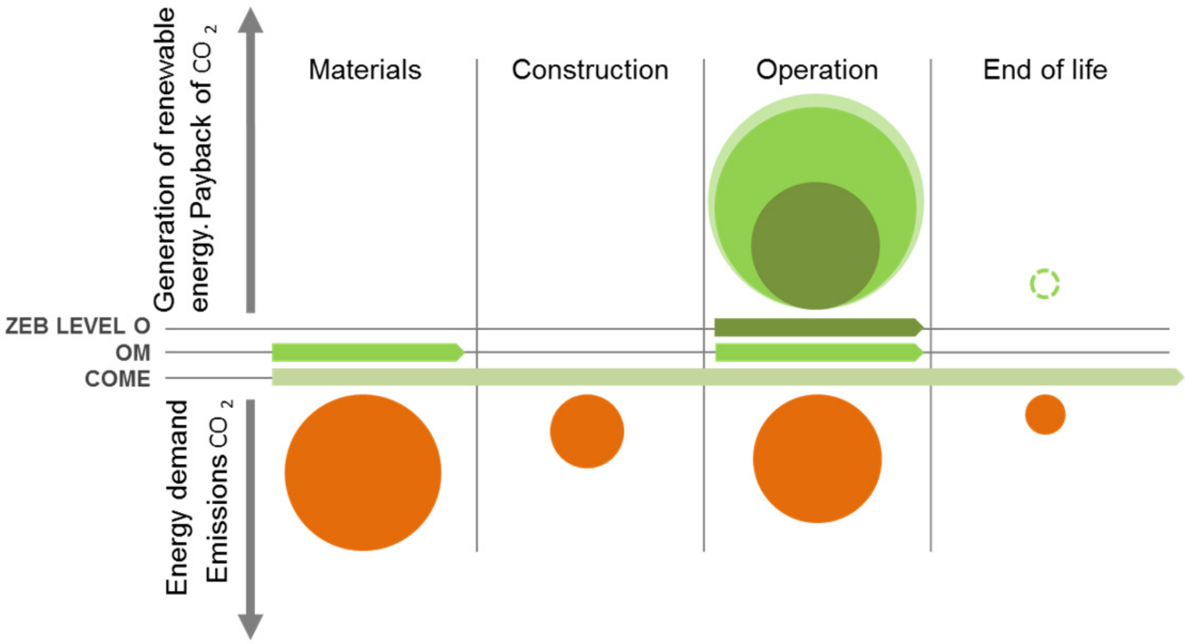


Figure 1.1 Three different ZEB ambition levels in the current ZEB-definition

2. Building model

The initial concept for the single family house is essentially based on state-of-the-art technologies already available on the market. Firstly, the space-heating demand is limited by using a highly-insulated envelope while the cooling load is restricted by implementing passive strategies. Secondly, energy-efficient building services are applied to minimize the energy use. In fact, an air-to-water heat pump is combined with solar thermal collectors through a storage tank so that both systems contribute to cover the thermal load (i.e. the domestic hot water and the space heating). Thirdly, a PV system is implemented to offset the emissions from operation and the embodied emissions. From a functional and architectural point of view, it has also been decided to limit the PV installation to the horizontal roof. Less sensitive to shading, the solar thermal collectors are placed on the south vertical façade to leave the horizontal roof available for PV.

Table 2.1 Areas and volumes for the residential building

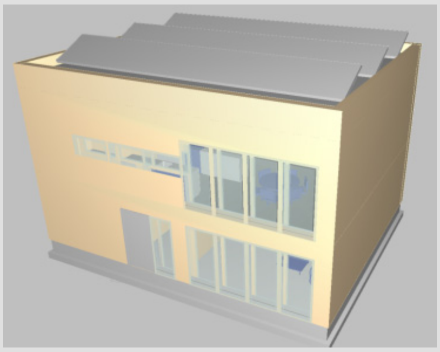
No of floors	**2**	
Floor area [m^2]	160	
Window area [m^2]	36	
Annual energy demand [MWh/year] -heating -cooling -electric	 4,1 0 7,2	

Table 2.2 Specification for the building envelope

	Values	**Solution**
External walls	U = 0,12 W/m²K	Timbered wall with 350 mm insulation.
External roof	U = 0,10 W/m²K	Compact roof with approximately 450 mm insulation.
Slab on ground	U = 0.07 W/m²K (U = 0.06 W/m²K)	Floor construction with 500 mm insulation. U- value in brackets takes into account the thermal resistance of the ground.
Windows	U = 0,65 W/m²K	Three layer low energy windows, with insulated frame.
Doors	U = 0,65 W/m²K	Well insulated doors.
Normalized thermal bridge value	ψ" = 0.03 W/m²K	Detailed thermal bridge design
Air tightness	N50 < 0,3 ach@50 Pa	Detailed design of a continuous vapour and wind barrier, good quality craftmanship and pressure testing of the building in two stages (when the windbarrier is mounted and when the building is finished).

Table 2.3 Specification for the HVAC installations

	Values	Technical solution
Heat recovery	η = 85 %	Rotary wheel heat exchanger.
Specific fan power	SFP = 1,0 kW/(m³/s)	Low pressure air handling unit (AHU) and low pressure ducting system.
Installed cooling capacity	Q''_{cool} = 0 W/m²	No cooling
Installed heating capacity	Q''_{heat} = 18 W/m²	Installed capacity for hydronic floor heating and radiators.

Table 2.4 Renewable energy systems for the residential concept building

	Residential
Vertical solar collector	8.3 m² (3374 kWh/a)
Air/water heat pump	7 kW
Solar cells on the roof	69 m² (11,3 MWh/a)

3. Energy and CO_{2eq} Calculations

The method used in the analysis of the energy concept and emissions from operation of the residential building consists of the following steps:

1. Calculation of the net energy budget (net demand)
2. Splitting of the demand into electric, thermal heating and thermal cooling demand
3. Calculation how the thermal energy supply meets the thermal demand (heating and cooling)
4. Calculation of the gross delivered energy, and the related CO_{2eq}-emissions for operation

The emission from the building needs to be balanced (offset) by renewable electricity production (e.g. PV), which is either used for self-consumption (reducing delivered electricity) or exported electricity to the grid. The goal of these calculations is to estimate and thereby get an overview of the largest impacts of the embodied greenhouse gas emissions connected to the ZEB -concept for a residential building. The method continues with the following steps:

5. Calculation of the CO_{2eq} emissions from both operation and materials
6. Design of the on-site electricity production and calculation of the total life cycle CO_{2eq} balance

Step 6 gives the answer if the PV-production meets the (different) ZEB-definition levels.

The results from the steps 1-5 are presented in figure 3.1. The total emissions from operation and materials are presented as annualized values. The embodied emissions from materials corresponds to 7.2 kgCO_{2eq} /m^2 per year and 59 % of the overall emissions and emissions from operation results in average annual emissions of 5.0 kgCO_{2eq} /m^2 per year.

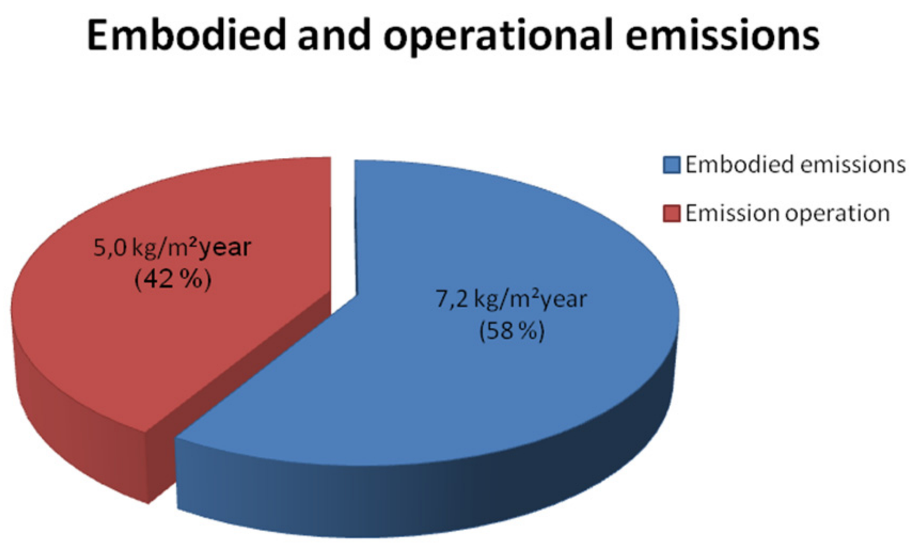


Figure 3.1 Embodied and operational emissions for the building

The results from the calculations of the CO_{2eq} balance is presented in figure 3.3. As illustrated in figure 1.1, the ZEB ambition level is decided based on to what extent the onsite renewable energy generation offsets emissions. In this study, electricity production from PV shall offset the emissions from materials and from operation of the building. Figure 3.3 shows that the PV production offset emissions from operation, but the electricity generation is not sufficient to also compensate for embodied emissions in materials.

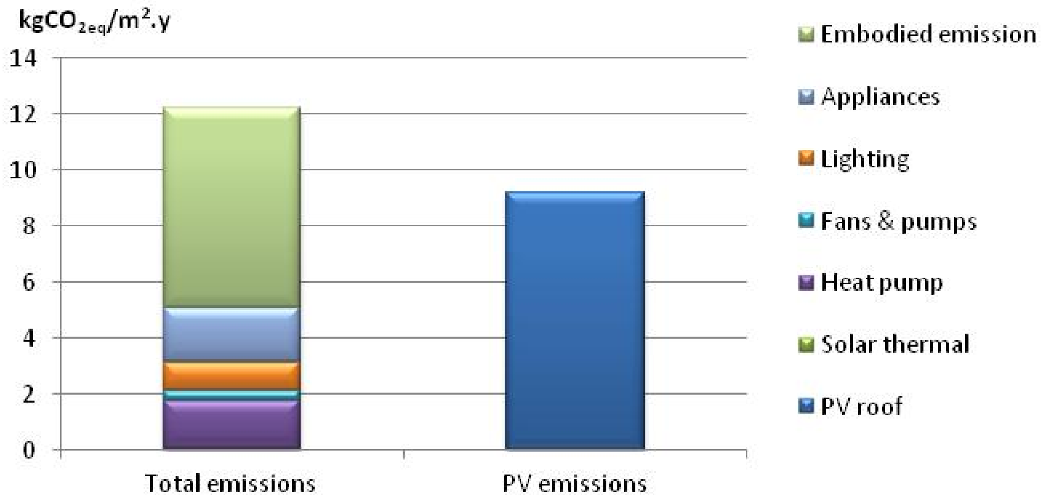


Figure 3.2 CO_{2eq} balance between embodied- and operational emissions with emissions balanced by PV electricity production using roof mounted PV.

4. Embodied Energy and Greenhouse Gas Emission

4.1 Method

In the first report of this work, the embodied emissions of the materials in the ZEB concept residential building were calculated to provide an overview of embodied emission using traditional materials. The study included materials in the envelope, ventilation & heating systems, as well as those associated with the renewable energy system, such as the photovoltaic panels and solar thermal units. The objective was to identify the key materials and components in the ZEB residential concept model which contribute the most to the embodied greenhouse gas emissions. The full details of this work can be found in ZEB report no.9 [1]. The sensitivity analysis is performed by identifying the materials responsible for the highest emissions.

In addition the sensitivity study investigates the influence of CO_{2eq}-factors for electricity in the operational phase on the emission balance. Furthermore, the analysis discusses the energy consumption of electric appliances and how it could be reduced through more efficient products, especially the so-called hot-fed machines (i.e. washing machines, tumble dryer and dishwasher).

4.1 Overview, goal and scope

The goal of this work is to investigate the effect on embodied emissions of materials and the overall performance of ZEB concept residential building, of using specific Norwegian EPD data instead of generic Ecoinvent data. In the first step, the generic Ecoinvent data for the selected materials are replaced with Norwegian EPD data where available. Concrete, insulation, plasterboard materials EPD data have been selected for this sensitivity study since these are responsible for the highest emissions apart from PV. Even though the embodied emissions from PV contribute the most emissions, they are not included in this analysis due to the limited information. Instead the influence of different PV technologies and different module orientations on the embodied and avoided emissions is incorporated from the work presented by Good et el.(2014) at the Eurosun conference [10]. Wood was also selected in this sensitivity study to study the benefits of using locally resourced materials using Norwegian EPD data.

A functional unit of 1 m^2 of heated floor area (BRA) in the residential building over the 60 year estimated lifetime of the building is used. The results are presented for emissions on an annual basis, where the functional unit of 1 m^2 is divided by the building lifetime. The estimated service lifetime of the different materials and components is mainly based on the guidelines from different product category rules.

The analysis is limited to cradle-to-gate for the material emissions (product stage: A1-A3) and replacement (B4) has been included as illustrated in Figure 4.1. below.

System boundaries (X=modules included in the study)																			
A1–A3 Product stage			A4–A5 Construction Process stage		B1–B7 Use stage							C1–C4 End-of-life				D1–D4 Benefits and loads beyond the system boundary			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D1	D2	D3	D4
Raw material supply	Transport	Manufacturing	Transport	Construction installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction demolition	Transport	Waste processing	Disposal	Reuse	Recovery	Recycling	Exported energy /potential
X	X	X						X											

Figure 4.1 System boundaries with respect to life cycle stages covered in the study according to EN 15804 [11].

4.1 Life cycle inventory

All amounts, volumes and masses in this study are based on the original concept report. The life cycle inventory data for the sensitivity analysis of embodied emissions of concrete, insulation, plasterboard and wood are based on the emission data from Norwegian EPD's. An EPD are concise and transparent documents, made on the basis of LCA and product category rules (PCRs) that summarize the environmental profile of a component, a finished product or service in a standardized and objective manner to enable purchasers and users informed comparisons between products. If PCRs for the same category from different program operators are made consistent, the declarations that originate from them can be made comparable [12].

4.2 Choice of emission factor for electricity mix

The choice of emission factor used for the electricity mix when conducting EPDs for building materials varies between different consultants and researchers. According to Holthe et al.[13], some researchers and consultants use the production/consumption electricity mix for Norway based on an average for the last three years while others use the Nordic electricity mix with a higher emission factor. Currently there is no consensus on which electricity mix should be used for Norwegian EPDs other than that the emission factor used for electricity in the production of the material should be stated on the EPD.

5. Sensitivity Analysis of CO_{2eq} Emissions

5.1 Embodied emission

5.1.1 Concrete

The concrete exists in the foundation and ground works, and apart from PV, was one of the materials driving the highest emissions in the original study of the residential concept building. The Norwegian EPD data for Betong Øst produced in Norway based on 1 m^3 of product, according to precast concrete PCR [14], is used for the sensitivity analysis (Table 5.1).

Table 5.1 Concrete materials used for the sensitivity analysis.

Concrete	Process	Place of Production	Density (kg)	Electricity mix	Embodied emissions (kg CO_2eq/m^3)	Reference
ZEB original data	Concrete, normal, at plant/CH U ZEB	Switzerland	2380	CH U	261,2	[3]
Norwegian EPD	Ferdigbetong B25M60	Norway	2358	Nordpool	189, 9	[15]

5.1.2 Insulation materials

The use of glass wool insulation in the outer and inner walls, as well as, EPS insulation in the ground floor slab and the roof are also one of the highest contributors to the overall embodied emissions from the original study of the residential concept building. The Norwegian EPD data for Glava glass wool and EPS, produced in Norway based on a mass (kg) of insulation material needed to cover a 1 m^2 of area of product (at a thickness that gives a design thermal resistance (R) of 1 m^2K/W) are used in this calculation according to the PCR for insulation materials [16]. The emission data given in the EPD are converted to 1m^3 of the insulation materials. The comparison of embodied emission between the original study of the residential concept building and the EPD switch is presented in Table 5.2 below.

Table 5.2 Glass wool and EPS insulation materials used for sensitivity analysis.

Insulation		Place of production	Thermal conductivity (W/mK)	Density (kg/m^3)	Electricity mix	Embodied emissions (kg CO_{2eq}/m^3)	Reference
ZEB original data	Glass wool mat, at plant	Switzerland	-	40	CH U	59,6	[3]
Norwegian EPD	Glava glass wool	Norway	0.035	16.5	NORDEL	21,14	[17]
ZEB original data	Rigid EPS Polystyrene foam slab, at plant	Europe	-	30	RER	126,3	[3]
Norwegian EPD	EPS isolasjon (trykkfasthet 80)	Norway	0.034	15	ENTSO-E	64,71	[18]

5.1.3 Plasterboard

The plasterboard to be substituted is included in the outer and inner walls, structural deck and outer roof. In the Norwegian EPD, the emissions data is given for $1m^2$ of plasterboard according to PCR for building boards [19]. The emission data given in the EPD are converted to $1m^3$ of the plasterboard for comparison with the emissions given in the original study (Table 5.3).

Table 5.3 Plasterboard materials used for the sensitivity analysis.

Material Input		Material Process	Place of production	Density (kg/m^3)	Electricity mix	Embodied emissions (kg CO_{2eq}/m^3)	Reference
ZEB original data	Plasterboard (outer walls)	Gypsum plaster board, at plant/CH U	Switzerland	900	CH U	315	[3]
Norwegian EPD		Norgips Standard Type A (STD)	Norway	720	Norwegian production mix from Ecoinvent v2	168	[20]
ZEB original data	Plasterboard (Inner walls)	Gypsum plaster board, at plant/CH U	Switzerland	900	CH U	315	[3]
Norwegian EPD		Norgips Standard Type A (STD)	Norway	720	Norwegian production mix from Ecoinvent v2	168	[20]

5.1.4 Wood

The wood to be substituted includes the loadbearing, solid timber beams in the outer walls, structural deck and outer roof. The substituted wood also includes the wood cladding in the outer wall and wood batons in the outer roof.

In the Norwegian EPD, the emissions data is given for 1 m^3 of the timber loadbearing structure, the pine wooden cladding and battons according to PCR for wood and wood-based products for use in construction are used for the sensitivity analysis [21] (Table 5.4).

Table 5.4 Wood materials used for the sensitivity analysis

Material Input		Material Process	Place of production	Density (kg/m^3)	Electricity mix	Embodied emissions (kg CO_{2eq}/m^3)	Reference
ZEB original data	Load bearing timber beam (outer wall, structural deck, outer roof)	Massivholz Fichte / Tanne / Lärche, Skandinavien, sägerau, entrindet	TBC	765	Scandinavia	68.85	[3]
Norwegian EPD		Structural timber of spruce and pine	Norway	420	Norwegian mean supply electricity mix from 2008-2010	53	[22]
ZEB original data	Wood pine cladding (outer walls)	Sawn timber, softwood, planed, air dried, at plant / RER U	Europe	500	RER	85	[3]
Norwegian EPD		Norwegian sawn dried timber (pine) used as beams, joists, studs, interior and exterior cladding	Norway	450	Norwegian consumption mix at medium voltage for 2008-2010	41	[23]
ZEB original data	Wood battons (outer roof)	Sawn timber, softwood, planed, air dried, at plant / RER U	Europe	500	RER	85	[3]
Norwegian EPD		Norwegian sawn dried timber (pine) used as beams, joists, studs, interior and exterior cladding	Norway	450	Norwegian consumption mix at medium voltage for 2008-2010	41	[23]

5.1.5 Results

The reduction in emissions resulting from the switch to specific Norwegian EPD data compared to those used in the original ZEB residential building using generic Ecoinvent data, is shown in Figure 5.1 below.

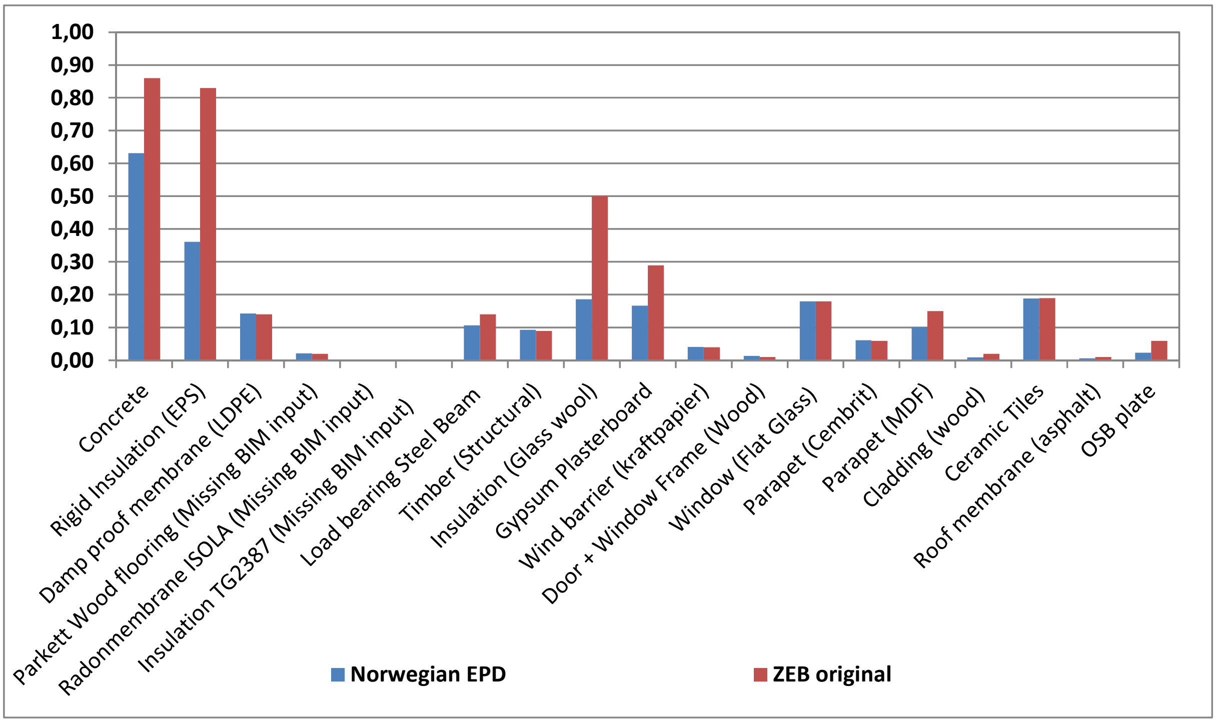


Figure 5.1 CO_2 emission comparisons between ZEB original study and EPD switch for main materials inputs.

The overall results show that by identifying the materials responsible for the highest emissions such as concrete, mineral wool and EPS insulation, plasterboard (and wood even though this is not a high emitter) in all the building components, the total embodied emissions for these materials can be reduced from the baseline of 7,2 kg CO_{2eq}/m^2 BRA/year to 5,8 kgCO_{2eq}/m^2 BRA/year when the Norwegian EPD data was substituted for the generic data. Although, this reduction is largely as a result of the Norwegian EPD using a much lower emission factor for the Nordel electricity mix and that the material efficiency, process technique used, heat energy and other factors can also play a crucial role.

5.2 PV system

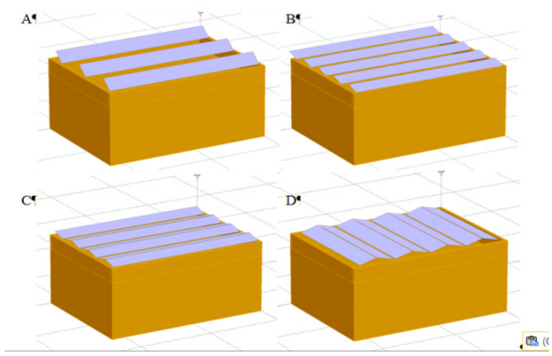
The results presented in this section are extracted from the work of Good et al., 2014 [10]. It was found that the embodied emissions from the PV system are a large contributor (29 %) to the overall emissions from the original study of the concept building. The sensitivity analysis evaluates if other PV technologies with lower embodied emissions give a positive contribution to the emission balance even though these technologies give a lower energy output.

Three different PV technologies (monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si) and CIS thin film), and four different module layouts for flat roofs are evaluated. The characteristics of the selected modules are shown in Table 5.5 and Table 5.6. Emissions data from the Ecoinvent v.2.2 database [3] was used for the calculations based on 1 m^2 of PV panel with frame. The emission balance was calculated with two different energy grid factors: the ZEB factor assuming a large decarbonisation of the EU electricity grid (0.13 kgCO_{2eq}/kWh) and the current EU factor (0.45 kg CO_{2eq}/kWh).

Table 5.5 Characteristics of the three PV modules used in the simulations.

PV technology	Module dimensions	Module area	Rated power	Efficiency	Embodied emissions per m² of panel
Mono-Si	983 x 1476 mm	1.45 m²	223 W_p	15.4%	199 kg CO_2eq/m²
Poly-Si	970 x 1630 mm	1.58 m²	210 W_p	13.3%	160 kg CO_2eq/m²
CIS thin film	630 x 1190 mm	0.75 m²	75 W_p	10.0%	123 kg CO_2eq/m²

Table 5.6 Overview of the four alternative design options for the PV system on the flat roof.

Design option	Azimuth of modules	Tilt angle of modules (°)	Description
A	South	40	
B	South	15	
C	South/North	15	
D	East/West	15	

The result when the two grid factors are applied to the energy yield of the PV modules is shown in Figure 5.2.

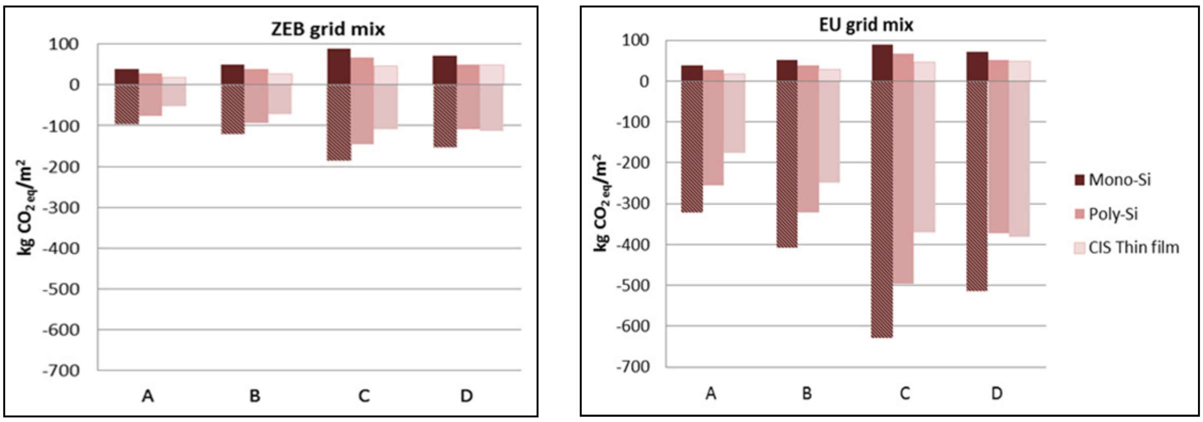


Figure 5.2 The embodied energy of the PV system (positive on the vertical axis) and the avoided emissions from the grid (negative on the vertical axis) of the systems for two different grid mixes.

The results show the avoided emissions are much larger when the EU grid factor is used (the embodied emissions are independent of the grid factor). The EU grid factor represents a grid with higher associated emissions than the ZEB grid factor, i.e. a lower share of renewable energy. This means that the electricity in the grid represented by the ZEB factor is already relatively “green”, and consequently the effect of replacing it with renewable energy is smaller in terms of avoided emissions.

Design option A, with optimally inclined (40°) and oriented modules, had the highest energy yield per installed module power (kWh/kW_p). The CIS modules had the highest ratio between energy output per module and embodied emissions. Nevertheless, due to the limited installation area available on the roof, the most favourable systems in order to reach a zero emission balance were found to be the ones with the highest energy density, i.e. energy output per roof area. These were the systems with a high number of modules at low inclination (design options C and D), and modules with highest efficiency (mono-Si). It should be noted that this was also the system with the highest amount of embodied emissions, and also included north-facing modules which had the lowest energy yield per module.

5.3 Emissions from operation of electric appliances and hot-fed machines

The baseline ZEB concept assumed a yearly electricity consumption of 2388 kWh based a simple but realistic estimate. This represents a specific energy consumption of 14.9 kWh/m²year which is 14% lower than the standard value used in the Norwegian standard NS3031. Given the high share of electricity use from appliances, it is worth investigating further their influence.

Table 5.7 Yearly electricity use per appliance for the baseline ZEB concept, the Remodece [24] and Swedish surveys [25]: the final column evaluates the total electricity use based on the Remodece study and a same appliance ownership as the ZEB baseline case.

Appliances	Baseline ZEB concept	Remodece (EU)	Swedish survey	ZEB updated
Dishwasher	234 kWh	234 kWh	236 kWh	234 kWh
Tumble dryer	320 kWh	347 kWh	131 kWh	347 kWh
Washing machine	189 kWh	184 kWh	213 kWh	184 kWh
Refrigerator	175 kWh	384 kWh	196 kWh	-
Freezer	234 kWh	543 kWh	372 kWh	-
Fridge with freezer	-	451 kWh	525 kWh	451 kWh
Oven	160 kWh	401 kWh	545 kWh	401 kWh
TV-LED	76 kWh	-	-	76 kWh
TV-CRT	-	124 kWh	-	-
Laptop IT	-	56 kWh	36 kWh	-
Desktop IT	-	276 kWh	342 kWh	-
Ironing, hover, …	-	147 kWh	78 kWh	147 kWh
Other	1000 kWh	238 kWh	102 kWh	238 kWh
Total	**2388 kWh**			**2182 kWh**

The Table 5.7 reports on the assumption made on the annual electricity appliances in the baseline ZEB concept. It can be compared with the results of the large measurement campaign Remodece [24]. The average consumption of electric appliances has been established based on a large-scale measurement campaign performed in European households. Almost no distinction is made between appliance efficiency (or labeling) and the value is thus representative of the existing stock of electric appliances. Furthermore, it does not distinguish between the different types of use. In parallel, results of a Swedish measurement campaign based on 200 households are reported [25]. Both Remodece and this Swedish study give similar results and are based on comparable methodologies. These values fit with the assumptions from the ZEB baseline case. It confirms that the ZEB baseline case is representative for average electricity consumption without particularly integrating best equipment with high performance. Furthermore, for a same type of equipment, large variations of yearly electricity consumption exist between households (again as a function of the equipment performance and specific use of occupants). The difference between ZEB baseline (i.e. 2388 kWh) and the Remodece based consumption (i.e. 2182 kWh) is significantly smaller compared to these variations. In other words, this difference is small compared to uncertainties and the variance of energy consumption within each category of equipment.

A fully consistent approach would first focus on a reduction the energy demand before maximizing the renewable energy production. Accordingly, in the ZEB concept, measures should both incorporate a minimization of the electricity needs and a maximization of the electricity production by photovoltaic panels, as it is done for the energy for heating. Nevertheless, it is difficult to quantity the reduction of electricity consumption that would result from a shift from standard electric appliances to high-performance products (i.e. only using best labels). This will not be discussed further but it is important to acknowledge that a substantial improvement can be done in the minimization of the electricity of appliances.

Among electrical loads, dishwasher, washing machines and tumble dryer directly convert electricity into heat. This is known to be a rather inefficient process from an exergetic point of view: high-grade energy is directly converted into low-grade. It would be more efficient to perform this heating using the hot-water produced by the heating system (here an air-to-water heat pump combined with solar thermal collectors). In that respect, three types of machines exist. *Hot-water fed* machines take the water directly from the domestic-hot water (DHW) system. This water is directly used to clean the crockery in a dishwasher or the clothes in a washing machine (i.e. it is the processing fluid). The water is only heated while the clothes, the crockery as well as the machine structure will be heated by the local electric resistance. Therefore, a limited amount of electricity from the machine can be substituted by hot water from the heating system. On the contrary, *heat-fed* machine are equipped by an internal heat exchanger coupled to the heating system. Heat can then be provided to the machine during all the washing or drying cycle, also heating the crockery, clothes or the structure of the machine. Then, hot-water from the heating circuit can substitute a significant part of the electricity (otherwise used by the machine). Heat-fed machine are thus different as they integrate a heat exchanger: it is not a standard product that is only operated in a different way (see Figure 5.3). The last category corresponds to tumble dryers or dishwashers equipped with a *built-in heat pump*. This technology is rather standard for tumble dryers while only a few models exist for dishwashers. For instance, Bengtsson [26, 27] reported a total electricity reduction of 64% for tumble dryers and 24% for an experimental dishwasher when both equipped with a built-in heat pump. Compared to heat-fed machines, models with a built-in heat pump do not require a connection to the heating system of the building. It therefore also avoids the distribution heat losses from the heating system to the machine. Nevertheless, in the case of heat-fed machines, the heat does not necessarily need to be produced by a heat pump. Alternative generation systems can be used such as a boiler, solar thermal systems.

Figure 5.3 Heat fed washing machine and clothes dryer from ASKO® with built-in water-to-water and water-to-air heat exchangers, respectively (in orange)

The following discussion is based on heat-fed machines. The number of scientific investigations on these machines is in fact limited. The following considerations are essentially based on the work of Tomas Persson and ASKO® [28-31]. Evaluating the electricity saving can be complex as it is dependent on the available temperature at the heating system, the program applied for the machine (e.g. Eco, Quick or Auto) and quantity of clothes and their initial humidity or the amount of crockery. Standard tests in laboratories should be distinguished with test during real operation. Using an inlet temperature of 80°C, the electricity saved per cycle by the washing machine is 81%, 80% for the dishwasher and 87% for the clothes dryer during laboratory measurements and a standard program. Nevertheless, the heat pump can only produce hot water up to 55°C. With an inlet temperature of 55°C, the electricity saving falls to 55% for the washing machine, 50% for the dishwasher and 78% for the clothes dryer. The internal electric resistance in the machines should provide for the rest. In the aforementioned numbers, the energy used to produce the hot water is not accounted for: it translates only how much of the electricity provides by the direct electric resistance can be replaced by hot water. These values were obtained during laboratory measurements, nevertheless, Persson has monitored lower value during field measurements. Final conclusions are at this stage unclear.

Summing up the yearly electricity consumption of the dishwasher (234 kWh), the washing machine (184 kWh) and the dryer (347 kWh) leads to a total of 765 kWh of electricity using standard technology. Assuming laboratory performance and water at 55°C, it can be reduced to 117 kWh, 156 kWh and 168 kWh, respectively; a total of 273 kWh instead of the initial 765 kWh. The remaining 491 kWh combined with additional distribution losses should be produced by the heating system (i.e. the heat pump or the solar thermal collector). Taking the yearly average temperature at Oslo (3.4°C) and the 55°C generation temperature, the heat pump has a COP of 2.5. Only a detailed simulation or measurement campaign would enable to determine the heating system efficiency to provide this hot water at 55°C all-your round. Therefore, a 2.5 seasonal efficiency of the heat pump is taken as a rough approximation. The resulting electricity for heating is thus 198 kWh. In total, the estimated electricity used with hot-fed machines is 471 kWh instead of the 765 kWh using conventional machines: ~300 kWh are thus saved, or about 1.8 kWh/m².year. Assuming the ZEB *Ultra-Green factor* for electricity of

132 gCO_{2eq}/(kWh/year), this corresponds to ~0.24 $kgCO_{2eq}$/(m².year). This approximation suggests that a significant improvement should be expected for the ZEB emission balance using heat-fed machines.

As a conclusion, the question of the reduction of the electricity use for household appliances is still open. The baseline scenario used so far corresponds to averaged electricity consumption without any attempt for reduction. The potential of reduction seems nonetheless large and deserves extended investigations. This field of investigation essentially depends on electrical engineering community. Finally, the use of heat-fed machines can reduce the consumption of the dishwasher, washing machine and the clothes dryer of about ~40% in total (neglecting the distribution heat losses). Normalizing the baseline electricity consumption for appliances to the Remodece values and including hot-fed machines, the value can be reduce from 2388 kWh to 1850 kWh. The reader should be aware that both values are prone to a large uncertainty and variance.

5.4 CO_{2eq} factors for grid electricity during operation

The baseline analysis of the ZEB residential concept has been based on a CO_{2eq} factor of 132 gCO_{2eq}/kWh for the electricity from the grid. It is essentially assumed that the factor is *yearly-averaged*, meaning that it does not account for variations within a year and it is an average value over a lifetime of 60 years. Furthermore, this factor is also considered as *symmetric* in the sense that the same factor is used for the electricity delivered from grid and exported to the grid. As the CO_{2eq} emissions balance includes embodied emissions, it is consistently based on the building lifetime. Yearly CO_{2eq} factor are thus required for the 60 year expected lifetime of the building. Accordingly, a scenario is therefore required for the evolution of the electricity grid for these next 60 years.

In this context, the baseline factor of 132 gCO_{2eq}/kWh is based on a specific scenario termed *Ultra-Green*. It assumes that the Nordic and European grids will be strongly interconnected and that a massive de-carbonization of the European electricity grid will take place in the next 40 years, see Figure 5.4. It is in good agreement with the objective of the European Union. In practice, the 132 gCO_{2eq}/kWh is taken as the 60-year average of this evolution, explaining its relatively low value. Even though realistic, it is worth investigating the performance of the ZEB concept as regards alternative scenarios for the CO_{2eq} factor. This has been investigated in detailed in Georges et al. [32]. The reader is invited to consult this work for extended explanations. Only the main results will be reported here below.

Alternative scenarios to the *Ultra-Green* are:

- The CO_{2eq} factor for European grid of today taken as constant for the next 60-years. It is termed *ZEB current EU* and has a value of 361 gCO_{2eq}/kWh.
- The CO_{2eq} factor for European grid of today taken as constant for the next 60-years but based on the UCTE report and including elements of Life Cycle Assessment for the grid. It is termed *UCTE current* and has a relatively high value of 531 gCO_{2eq}/kWh.
- The Norwegian grid is assumed isolated from the rest of Europe and the current Norwegian CO_{2eq} factor is assumed constant for the next 60 years. This scenario is termed *NO current* and has an extremely low value of 38 gCO_{2eq}/kWh.

The balance of emissions can be established for each factor, as reported in Figure 5.5. The embodied emissions are taken from the baseline scenario with a value of 7.2 $kgCO_{2eq}$/m². The large influence of the CO_{2eq} factor is obvious. Two aspects can be investigated: (1) the relative importance of embodied emission (EE) compared to CO_{2eq} emissions for the building operation (EO), and (2) the balance of CO_{2eq} emissions during the building lifetime:

1. With a low CO_{2eq} factor for electricity, such as using the *ZEB Ultra Green* or the *NO current*, EE are dominant over EO. This proves that a significant effort should be done to reduce embodied emissions in material. If is the European grid is not de-carbonized, CO_{2eq} factors will remain high and the EO will continue to be significant compared to EE.
2. As regards balance of CO_{2eq} emissions, the ZEB-OM level is not reached using the baseline scenario (i.e. the *ZEB Ultra-Green*) or the current Norwegian factor. This can be easily explained. The building has a net electricity export to the grid over one year (i.e. more export than import). If this export is credited by a relatively low CO_{2eq} factor, it is difficult to counterbalance for embodied emissions (based on the relatively high CO_{2eq} factor of today). In other words, as the European grid is getting "greener", the interest to offset electricity of the grid using onsite renewable electricity production is reduced. Nevertheless, one should be very careful when interpreting these conclusions. In practice, the on-site electricity production of buildings will be a part of the solution to de-carbonize the European grid. The problem should not be artificially decoupled (as it is in fact done when performing a balancing of emissions only including the building). Even if the ZEB-OM balance is not reached, the contribution of this category of building remains important (as a part of the solution to de-carbonize the grid). If one assumes Norway as isolated, what is then the interest to replace electricity coming from hydroelectricity to onsite electricity production? This question is essentially true but it is rather assuming Norway as isolated that does not make really sense. On the contrary, if the European grid continues with high CO_{2eq} factors, the export of electricity from the building will offset a relatively large amount of CO_{2eq} emissions. Consequently, the ZEB concept will be able to reach the ZEB-OM balance (including both EO and EE). The worst the CO_{2eq} factor from the grid, the easier it is to reach this balance.

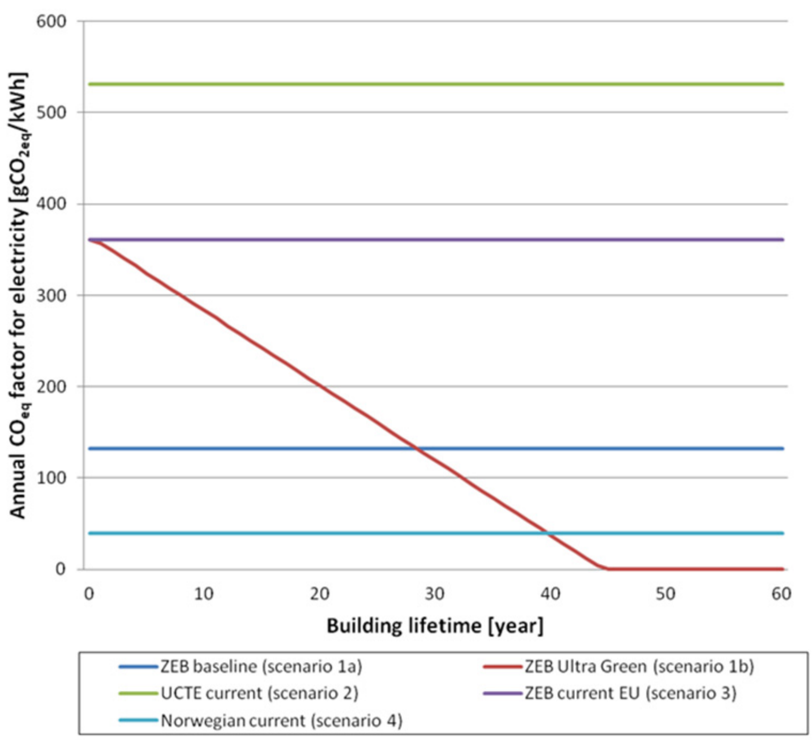


Figure 5.4 Different scenarios of annual CO_{2eq} emissions factors (gCO_{2eq}/kWh) for the next 60 years [32].

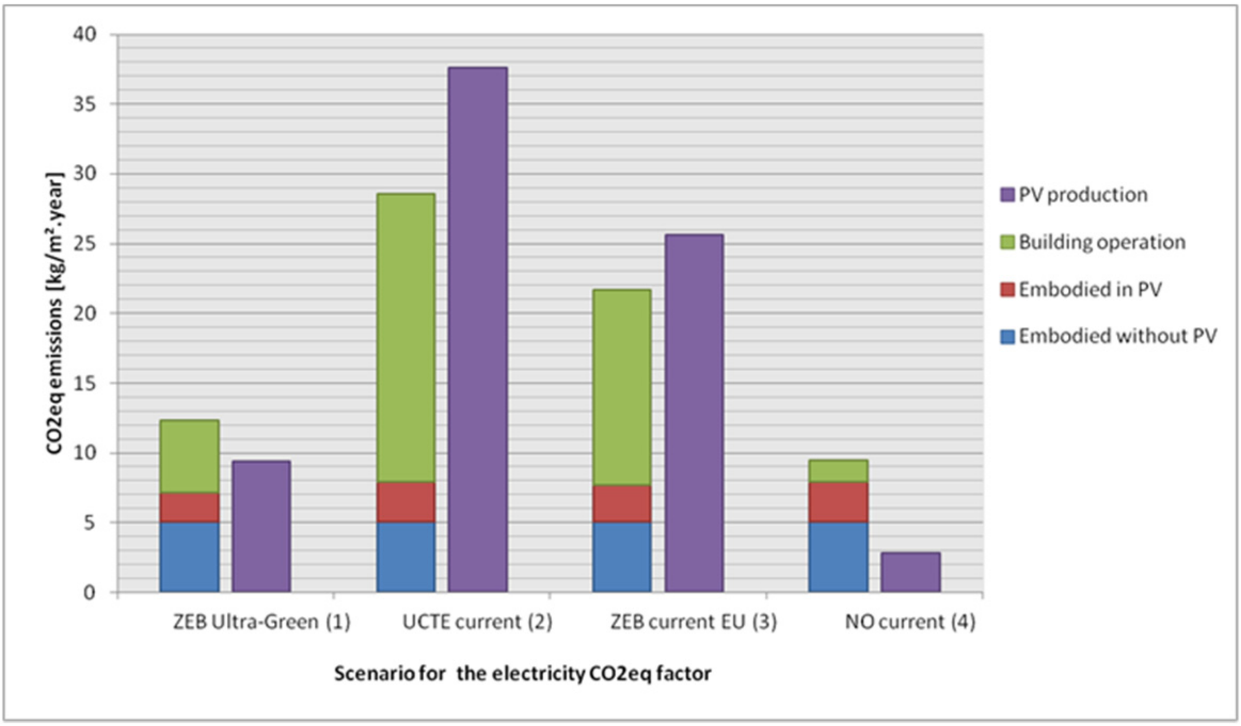


Figure 5.5 Annual CO_{2eq} emissions and offset from PV for the different CO_{2eq} factors for the electricity [32].

Based on these conclusions, it proves that it is important not to analyse the performance of a ZEB only based on the balance of emissions. It is also important to look at the efficient in terms of CO_{2eq} emissions (EE+EO). Furthermore, it is also imperative to consider how the ZEBs contribute to the improvement of the electricity grid (essentially through their local renewable energy production but also through the flexibility they can provide to grid, using for instance *demand side management*). Finally, embodied emissions are significant and can be even dominant in the context of a low-carbon grid. They thus deserve to be minimized.

5.5 Modified model

In the modified model (Table 5.8), the embodied emissions from materials have been reduced from 7.2 $kgCO_{2eq}/m^2year$ to 5.8 $kgCO_{2eq}/m^2year$. Emissions for the different building components contained in the Table of Building Elements NS 3451 for ZEB original and the sensitivity study.

Building elements	**$kgCO_{2eq}/m^2$ BRA/year**	
	ZEB original	**Sensitivity study**
2 Building		
21 Groundwork and foundation	1.47	0.96
22 Superstructure	0.14	0.11
23 Outer walls	1.32	0.90
24 Inner walls	0.37	0.28
25 Structural deck	0.38	0.30
26 Outer roof	0.43	0.20
28 Stairs, balconies, etc	0.00	
29 Others (heating piping/radiator, hot water tank, heat pump, refrigerator fluid)	0.65	

Building elements	kgCO_{2eq}/m² BRA/year	
	ZEB original	Sensitivity study
3. Heating, ventilation and sanitation		
36 Ventilation and air conditioning	0.05	
4. Electric power		
49 Other electric power installations		
Photovoltaic panel, single Si,at plant/RER)	2.15	
Evacuated tube collector, at plant/GB	0.23	
Total	**7.2**	**5.8**

The electricity load can be reduced from the 14.9 kWh/m².year to 11.6 kWh/m² per year by essentially using more consolidated data for household appliances and hot-fed machines. This corresponds to an annual CO_{2eq} reduction of 0.24 kg/m².

The balance of CO_{2eq} emissions is changed when both the emissions from materials and operation are included together depending on the choice of the grid mix as shown and reported in Figure 5.6. below. It should be noted that the replacement scenario for PV uses the different electricity scenarios for future emissions, so the replaced PV is produced with 'cleaner' electricity and thus lower embodied emissions however dependent on the different scenarios.

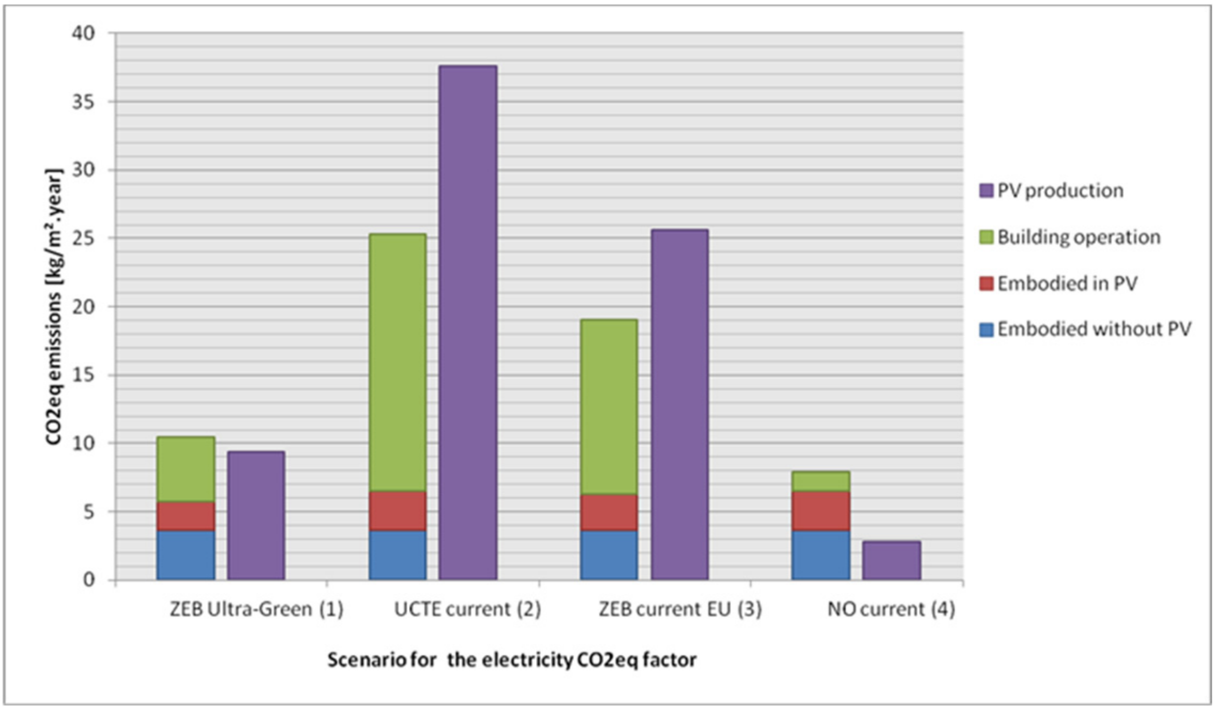


Figure 5.6 Annual CO_{2eq} emissions and offset from PV for the modified ZEB concept, for the different CO_{2eq} factors for the electricity [modified from original work published in 32].

The improvement is clearly noticeable but does not alter conclusions. It is nevertheless worth noticing that ZEB-OM is almost reached when the *ZEB Ultra-Green* CO_{2eq} factor is used. The magnitude of EE and EO is also significantly improved. In the *ZEB Ultra-Green* scenario, the largest improvement is due the reduction of embodied emissions.

6. Discussion, Conclusions and Further Work

6.1 Discussion and Conclusions

This report investigates the influence of using Norwegian emission data (from EPDs), using different CO_{2eq}-factors (for electricity in the operational phase) and electricity load from household appliances (using data for household appliances and hot-fed machines) on the overall ZEB residential building performance.

The results from the switch to specific EPD data shown in Figure 5.1 and Table 5.8, show a significant reduction in total embodied emissions for materials from 7.2 to 5.8 $kgCO_{2eq}/m^2$/per year. The embodied emission analysis presented here is transparent since the emission data are extracted from publicly available EPDs that are performed according to EN 15804.

However, it should be noted that these emissions reflect cradle to gate emissions (A1-A3) and replacement (B4) but do not reflect the even greater potential if calculated for cradle to grave emissions where the longer term benefits of wood as a carbon store can be seen. It should be made clear that emissions related to transport from cradle to factory gate (A2) are accounted for in our calculations but those emissions related to transport from gate to construction site (A4) have not been included. The true benefits of using specific data for those products produced in Norway would be seen if the system boundary is extended to include transport emissions.

It should also be noted that the results for the EPD switch are based on the emission factor calculated using the CO_{2eq} factor for the Nordel mix in the Norwegian EPD's compared to a much higher value used for RER or average European mix. As seen, for example in Table 5.4. In particular, as seen in the case of wood cladding and batons, this can result in a 75% reduction in emissions for a particular material. Similarly, a significant reduction in emissions can be seen in the switch from generic to specific Norwegian EPD data for concrete where the much lower CO_{2eq} factor for the Nordel mix is used in the calculations. Even if the calculation of embodied emission has uncertainties, preliminary results indicate significant reduction of embodied emissions by replacing generic data with specific data from EPDs.

The CO_{2eq} factor considered for the electricity imported and exported to the grid has a large influence on the net ZEB balance. For instance, the ZEB-OM balance is not reached in the context of a low-carbon grid which corresponds either to the Norwegian grid connected to the future de-carbonisation European grid, or to the current situation with a Norwegian grid that has some transmission capacity to Nordic countries, but are only to a limited degree connected to the European grid. In this context, the embodied emissions are higher than the emissions for the building operation during the 60-year lifetime. On the contrary, if the emission factor grid electricity is relatively high, a scenario corresponding to a Norwegian grid fully connected to a European grid without de-carbonization, the ZEB-OM balance is reached and the emissions for building operation dominate over embodied emissions.

When discussing the performance of ZEB, one should be very careful as this performance is not only limited to a balance of CO_{2eq} emissions. In fact, the overall ZEB performance is the combination of its energy efficiency, reduced embodied emissions and emissions for building operation, on-site renewable energy conversion, flexibility offered to the electricity grid (e.g. grid interaction), as well as, balance of CO_{2eq} emissions. By the way, in the context of a low-carbon grid, it is not because the ZEB-OM balance is not reached that the interest into the ZEB concept is essentially lost. For instance, ZEBs are considered necessarily to shift to this low-carbon grid due to their high energy efficiency, onsite renewables and the flexibility they can provide to the grid.

It was found that the PV system which generates renewable electricity to balance the emissions of the building is itself also a major source of embodied emissions. Four alternative installations and three types of PV technologies were studied in order to find a balance between emissions and energy output. Even though it had the lowest energy output per module and the largest value of embodied emissions, it was found that the system with low-inclination south/north facing mono-Si modules was the one that contributed most to the net avoided emissions of the building.

Due to high level of insulation of the building envelope, the electricity use of the household appliances becomes relatively large. Therefore, different options should be considered for its reduction. *Heat-fed machines* can be implemented for the washing machine, dishwasher and tumble dryer. The machine is then connected to the energy-efficiency heating system of the building through a built-in heat exchanger. Reliable reports on the performance of such systems are still limited. Nevertheless, based on the existing technical literature, a total yearly electricity reduction of ~40% could be expected for these appliances when using heat-fed technology.

6.2 Further work

Based on the analysis in this report, some of the issues that need further work are listed below.

- The embodied emission calculation was performed based on cradle to gate (A1-A3) and replacement (B4) emission data of concrete, insulation materials, plasterboard and wood using EPDs with lowest emission data. The calculation could be extended to consider worst case scenarios by using EPD data of the materials with highest emission. Moreover, incorporation the calculation by using EPD data for other building materials could show further reduction of the emission. Note that, EPDs from other countries (like IBU EPD) can be adopted for materials where Norwegian EPDs are not available, if the EPDs use the same PCR, structured following EN 15804 and do not contain substances that are not accepted in the Norwegian market.
- Extending the system boundary to include the transport to the building phase (A4) in further work, can identify the impact of emissions from transport.
- Furthermore, including the end of life phase is necessary in order to show the benefits during this stage for the replaced products, such as products with service lifetimes of 10, 15, 20 or 30 years which would highlight the benefits of using building materials that are recyclable or have the potential for energy recovery e.g. incineration of wood.
- There is further potential to reduce the embodied emission by considering the biogenic carbon stored in wood products during the production and use phase as well as fossil CO_2 emission substitution at the end of life phase.
- Using alternative building materials, for example replacing concrete with green concrete or replacing mineral wool with wood fibre insulation, should be included in the next step of the work.
- The electricity use for household appliances is prone to a large uncertainty and is essentially user-dependent. So far, the yearly electric consumption has been taken equivalent to the average equipment type, ownership and user-behaviour of the existing residential building stock. Further work is thus required to define the potential energy saving that would result from a shift of standard appliances to high-performance appliances with better energy efficiency. Users have also a strong influence on this electricity consumption while it becomes a dominant energy use between building services due to the high-level of thermal insulation of the envelope.

7. References

1. Dokka, T.H., Houlihan Wiberg, A.A., Georges, L., Mellegård,S., Time,B., Haase, M., Maltha,M., Lien, A.G., *A zero emission concept analysis of a single family house. ZEB Project report no 9, The Research Centre on Zero Emission Buildings (ZEB)*. 2013.
2. PRe´ Consultant. *SimaPro Life Cycle Analysis,* Simapro 7.3 (Version 7.3.). 2012, Amersfoort, the Netherlands.
3. Ecoinvent version 2.2. *Swiss Center for Life Cycle Inventories*. (2010)., Accessed from http://www.ecoinvent.ch/
4. ProgramByggerne. *SIMIEN, SIMulation of Indoor climate and ENergy use* (Version 5.0.14). 2012, Skollenborg. Retrieved from http://www.programbyggerne.no/SIMIEN
5. THERM software. No reference.
6. S. Vela, Polysun, 2012, 5.10.9, available from: http://www.velasolaris.com
7. PVsyst SA, PV-syst 5.62, Photovoltaic System Software 5.62, available from: http://www.pvsyst.com/en/
8. Dokka, T. H., Sartori, I., Thyholt, M., Lien, K.,&Lindberg, K. B. (2013c, 15-17 October). *A Norwegian Zero Emission Building Definition.* Paper presented at the Passivhus Norden 2013, Gothenburg, Sweden.
9. NS 3700, *Criteria for passive houses and low energy buildings - Residential buildings (in Norwegian)*. 2013, Standards Norway, Oslo, Norway.
10. Good, C., Kristjansdottír, T., Houlihan Wiberg, A.A., Georges, L., Hestnes, A.G. *A comparative study of different PV installations for a Norwegian net ZERO emission building concept* in *Eurosun conference*. 2014. Aix-les-Bains, France, 16-19 September.
11. EN 15804, *Sustainability of construction works Environmental product declarations Core for the product category of construction products*. 2012, European Committee for Standardization, Brussels, Belgium.
12. Ingwersen, W.W. and M.J. Stevenson, *Can we compare the environmental performance of this product to that one? An update on the development of product category rules and future challenges toward alignment.* Journal of Cleaner Production, 2012. **24**(0): p. 102-108.
13. Holthe, Kristin., et al., *KONSENSUS : Metode for miljøvurdering (LCA) av bygninger – dagens praksis og anbefalinger : Report from part 1 of the project Konsenus Arena. (in Norwegian)* 2011, Technical report from SINTEF Building and Infrastructure and Ostfold Research Company.
14. NPCR 020, *Product-category rules for Precast concrete products, NPCR 020*. 2012, The Norwegian EPD Foundation, Oslo, Norway.
15. NEPD 123N, *Ferdigbetong B25 M60 , Betong Øst, NEPD nr.: 123N*. 2013, The Norwegian EPD Foundation, Oslo, Norway.
16. NPCR 012, *Product-categoty rules for preparing an environmental declaration for product group Insulation materials, NPCR 012rev*. 2012, The Norwegian EPD Foundation, Oslo, Norway.
17. NEPD 221E, *EPD of Glava glass wool, NEPD nr.: 221E ver 2*. 2013, The Norwegian EPD Foundation, Oslo, Norway.

18. NEPD-322-185-NO, *EPD of EPS isolasjon (trykkfasthet 80), NEPD-322-185-NO*. 2015, The Norwegian EPD Foundation, Oslo, Norway.

19. NPCR 010rev1, *Product-categoty rules for Building boards, NPCR 010rev1*. 2013, The Norwegian EPD Foundation, Oslo, Norway.

20. NEPD00113E, *Updated Norgips Standard type A (STD), Plasterboard 12,5mm. NEPD00113E 2014*, The Norwegian EPD Foundation, Oslo, Norway.

21. NPCR 015, *Wood and wood-based products for use in construction, NPCR 015 rev 1. 2013*, The Norwegian EPD Foundation, Oslo, Norway."

22 NEPD-308-179-EN, *EPD of Structural Timber of Spruce and Pine, NEPD308179EN*. *2014*, The Norwegian EPD Foundation, Oslo, Norway.

23. *NEPD-307-179-EN, EPD of Sawn dried timber of spruce or pine, NEPD-307-179-EN. 2015,* The Norwegian EPD Foundation, Oslo, Norway

24 Sæle, H., Rosenberg, E., Feilberg, N., *State-of-the-art projects for estimating the electricity end-use demand*. 2010, SINTEF: Trondheim.

25. Enertech, *End-use metering campaign in 400 households in Sweden*. 2008, Swedish Energy Agency.

26. Bengtsson, P., *Increasing the value of household appliances by adding a heat pump system*, in *Department of Engineering and Chemical Sciences*. 2014, Karlstad University: Karlstad University Studies.

27. Bengtsson, P., J. Berghel, and R. Renström, *A household dishwasher heated by a heat pump system using a energy storage unit with water as the heat source.* International Journal of Refrigeration, 2015. 49: p. 19-27.

28. Persson, T. and R. Renström, *Fjärrvärmedrivna vitvaror: erfarenheter från utveckling, installationer och kostnadsberäkningar*. 2013, Svensk Fjärrvärme AB.

29. Zegers, F.T.S. and E.C. Molenbroek, *Field test of heat-fed washing machines and tumble dryers: Cadence Appendix K*. 2000, ECOFYS.

30. Persson, T. and M. Rönnelid, *Increasing solar gains by using hot water to heat dishwashers and washing machines.* Applied Thermal Engineering. **27**: p. 646-657.

31. Persson, T., *Dishwasher and washing machine heated by a hot water circulation loop.* Applied Thermal Engineering, 2007. **27**: p. 102-128.

32. Georges, L., Haase, M., Houlihan Wiberg, A.A., Kristjansdottir, T., Risholt, B. *Life cycle emissions analysis of two nZEB concepts.* Building Research and Information, 2015. 43(1): p. 83-93.

The Research Centre on Zero emission Buildings (ZEB)

The main objective of ZEB is to develop competitive products and solutions for existing and new buildings that will lead to market penetration of buildings that have zero emissions of greenhouse gases related to their production, operation and demolition. The Centre will encompass both residential and commercial buildings, as well as public buildings.

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www.glava.no

Protan
www.protan.no

Hydro Aluminium
www.hydro.com

Caverion Norge
www.caverion.no

ByBo
www.bybo.no

Multiconsult
www.multiconsult.no

Brødrene Dahl
www.dahl.no

Snøhetta
www.snoarc.no

Forsvarsbygg
www.forsvarsbygg.no

Statsbygg
www.statsbygg.no

Husbanken
www.husbanken.no

Byggenæringens Landsforening
www.bnl.no

Norsk Teknologi
www.norskteknologi.no

Direktoratet for byggkvalitet
www.dibk.no

DuPont
www.dupont.com

NorDan AS
www.nordan.no

Enova
www.enova.no

VELUX
www.velux.com

Entra
www.entra.no

www.zeb.no